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OPTIMAL EVALUATION OF FORMATION RESISTIVITIES USING ARRAY INDUCTION AND ARRAY LATEROLOG TOOLS

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Abstract

One of the perennial formation evaluation questions is that of selecting the optimal technique for determining formation resistivities. Since the early days of well logging two techniques have been in common use, induction and laterolog. Each has strengths and limitations that tend to complement the other. We review the latest selection methods in light of recent advances in both hardware and processing.

Developments in both induction and laterolog technology have advanced the state-of-the-art from relatively simple early tools to the sophisticated array measurements and associated post-acquisition processing available today. With these improvements the "overlap zone," where environmental conditions allow valid measurements by both induction and laterolog tools, has increased. Comparison of the tool responses in the overlap region displays the complementary nature of the measurements.

The primary selection criterion is based on borehole effects on the measurements. We have developed a Web-based job planner which compares the operating ranges of the array induction and array laterolog tools. With the improved information content of the array measurements we can better define borehole effects and thus either flag or more accurately correct the data. Development of environmental log quality control for the induction measurements helps identify when the tool is out of its range. The result is improved accuracy and confidence in the resulting formation resistivities. This paper reviews the techniques and the improved data quality they yield.

Sensitivity to hitherto neglected environmental effects such as anisotropy and shale alteration have made comparison between induction and laterolog tools difficult in many situations. With the number of measurements made by array tools, one can now use the different sensitivities of laterolog and induction measurements to sort out these environmental effects.

In addition, advanced processing such as maximum entropy and 2D inversion helps explain apparent differences in the formation resistivities derived from the two measurements. Several field log examples show both the practical application of the selection methodology and the effect of post-processing on formation resistivity evaluation.

Introduction

Estimation of formation resistivities by induction and laterolog methods has seen significant advances in the last several years. Both techniques have evolved through the dual measurement phase (dual induction and dual laterolog tools) to the latest array measurements.

The AIT* Array Induction Imager Tool (Hunka *et al.*, 1990; Barber *et al.*, 1995) generates five inductive responses which have their 50 percentile integrated radial response points 10, 20, 30, 60 and 90 in. from the center of the borehole. Likewise, the HRLA* High-Resolution Laterolog Array tool (Smits *et al.*, 1998; Griffiths *et al.*, 1999) generates five galvanic responses with varying depths of investigation. The introduction of the HRLA tool has addressed many of the limitations of the dual laterologs (Smits *et al.*, 1995) by

- removing the need for a bridle
- improving combinability
- eliminating the Groningen and drillpipe effects
- reducing the shoulder-bed effect
- increasing the resistivity operating range.

Compared to the older dual-measurement tools, improvements in materials, electronics and processing have resulted in significant increases in the operating ranges of both the array instruments. The operational and petrophysical improvements delivered by these array tools have outdated the selection methodologies applicable to the dual-measurement tools (Suau *et al.*, 1972). BB

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Fundamentals

Formation resistivity evaluation depends on two basic physical principles: galvanic physics, in which current is focused into the formation to be measured, and inductive physics, in which electromagnetic excitation of the formation induces currents to flow.

Galvanic measurements have evolved into the laterolog family of tools. These require a conductive borehole environment so that the measure currents from the tool can traverse the borehole and enter the formation. Laterolog instruments respond to the *series resistance* of the various formation regions through which the measure currents pass.

Induction measurements have evolved into the array-induction family of tools. These can operate in a nonconductive borehole environment, making them the only option for formation resistivity evaluation in oil-based mud (OBM). Induction instruments respond to the conductivity of the formation in which the tool response is induced. Recalling that the addition of conductivities is equivalent to computing equivalent resistances in parallel, as shown in Figure 1, induction instruments can be regarded as being sensitive to the resistivities of the formation regions in *parallel*.

This concept of series and parallel equivalent resistances is fundamental to understanding the response of laterolog and induction instruments. In the simplest model of the borehole/formation environment, shown in Figure 2, the resistivities to which these instruments respond are lumped into three equivalent resistivities: R_m, R_{xo} and R_t. To derive the equivalent formation resistivities, R_{xo} and R_t, it is first necessary to account for the influence of the borehole on the response of the instruments.

Borehole Effects

The degree to which the borehole environment has an effect on the response of the instruments is a function of the ratio of formation to mud resistivity, borehole size, and position of the instrument in the borehole as well as the physics of measurement of the instrument. In the limiting case of a nonconductive borehole (i.e., OBM), laterolog instruments will not work while induction instruments will be almost unaffected by the borehole. At the other extreme, a large borehole with very salty water-based mud, the borehole environment will have considerably less influence on the laterolog instrument than on the induction. The latter will be strongly affected by the conductive borehole in parallel with the formation.

The extent to which accurate compensation for the borehole effect can be determined defines the extremes at which each instrument will yield a valid response with sensitivity to the formation. Figure 3 shows the screen of a Web-based job planner which indicates the valid operating ranges for the AIT and HRLA tools in an infinite, homogeneous, uninvaded formation. The instrument response limits vary according to the borehole size, tool position, and R_t/R_m ratio entered by the user. A red line is plotted between the R_t/R_m and R_{xo}/R_m values to indicate the resistivity range expected in a given interval. This allows the user to judge whether the resistivities fall in the AIT range, the HRLA range, or the overlap zone (as shown in the case in Figure 3), where environmental conditions allow valid formation measurements by both induction and laterolog instruments.

Induction Response

The borehole environment has different effects on the response of induction and laterolog instruments. The AIT tool measures R and X signals from eight arrays and forms logs that best distill the information content of the raw array data. This processing (Barber and Rosthal, 1991) uses the high spatial resolution of the shallow arrays to enhance the vertical resolution of the deeper measurements. Where the borehole environment degrades the response of the shallow arrays, the high spatial resolution data are lost. For this reason the vertical resolution of the computed responses also degrades (Barber *et al.*, 1999a). This is indicated by the three dashed lines on the chart in Figure 3. The region in the lower left corner of the chart indicates where all the AIT outputs are valid, including the 1-ft vertical resolution curves. In conditions that plot above or to the right of this line it is possible that the 1-ft logs are inaccurate because of the borehole effect on the shallow arrays. Moving up and to the right on the chart, the next line indicates the limit of validity of the 2-ft vertical resolution logs. Above and to the right of the third line, the 4-ft vertical resolution logs are no longer valid and the induction instrument is out of its operating domain. Note that the HRLA domain covers the majority of the zone outside the domain of valid AIT response (and vice versa).

The chart-based approach assumes a smooth borehole. When the borehole is very rough or the tool standoff inadequate, the shallow arrays can be degraded, rendering the high-resolution logs unusable. A rugosity-detection algorithm has been developed to detect this situation. A best resolution flag (R), shown in Figure 4, combines the chart logic and the rugosity algorithm to indicate the highest valid resolution for the array-induction data.

Boreholes can become magnetic through the use of iron-containing weighting materials. In addition, milling of casing to sidetrack can place the milled steel particles in the mud or mudcake. The response of induction instruments can be affected by the presence of magnetic material in the mud. A magnetic mud flag, M, also shown in Figure 4, indicates when this condition exists. Special processing which reduces the sensitivity to magnetic mud has been available for the past two years.

Laterolog Response

As with induction instruments, increasing borehole size and mud conductivity degrades the shallower measurements. However, since it is the physical distance between the monitoring electrodes on the sonde body that determines the vertical resolution of laterolog instruments, increasing borehole size or conductivity will render the shallow arrays unusable without affecting the vertical resolution of the deeper measurements (Smits *et al.*, 1998). In these conditions the shallower arrays become unusable because they are electrically shorted through a large and conductive borehole. In the case of the HRLA array, the shallowest curve, RLA1, will saturate or "flat-top" at a value defined by the R_t/R_m ratio, borehole size, and tool position. This shallow array saturation limit is displayed as a vertical solid line on the planner plot. For example, in the conditions shown in Figure 5, this corresponds to an RLA1 limit of 7370 ohm-m. RLA1 will be unreliable in formation resistivities above this value. Formation resistivities can be derived from the remaining four array responses.

Invasion Effect

The job-planner chart plotted in Figure 5 considers the formation to be infinite and uninvaded. The majority of real reservoirs, however, are invaded by some component of the mud during the drilling process. This creates the near-wellbore annulus of altered resistivity called the invaded zone, which is assigned the equivalent invaded zone resistivity, R_{xo}.

Consideration of the physics used in each of the instruments leads to the general rule of thumb that where $Rt > R_{xo}$ a laterolog instrument is preferred, while when $R_{xo} > R_t$ an induction instrument is preferred.

$R_{xo} > R_t$

As an example of the invasion effect, Figure 4 shows a thick sand in which both array induction and array laterolog data were computed. The job-planner plot for these conditions, shown in Figure 5, indicates that the HRLA tool is within its operating domain and that the 4-ft vertical resolution AIT curves should also be valid. Despite their validity the responses initially appear to indicate different uninvaded formation resistivities. The pad measured R_{xo} (RXOZ) response indicates that a high resistivity zone exists near the borehole wall.

The HRLA and AIT radial response plots, also available from the Web-based planner, shown in Figures 6 and 7, indicate that in these conditions the separation between the HRLA responses remains small until the invasion front is at least 2 in. into the formation. In addition the high-resistivity invaded zone affects all the laterolog responses, since they respond to the resistivities in series.

In contrast, the induction response is largely unaffected by the thin high-resistivity zone, with the majority of the AIT curves indicating a value close to R_t until the invasion radius becomes quite large. The induction instrument is sensitive to the high conductivity of the uninvaded zone, rather than the low conductivity of the invaded zone, and is relatively unaffected by the damaged layer. It should be noted that in most situations neither tool will "read" R_t directly, but will require some sort of inversion to determine R_t.

$R_{xo} << R_t$

The majority of reservoirs drilled with water-based mud have $R_{xo} < R_t$. Where R_t is greater than about 50 times R_{xo} the induction response is degraded by this extended zone of low resistivity in parallel with the high resistivity R_t. This ratio is also a function of hole rugosity, with the induction tool supporting a lower ratio in bad-hole conditions. Even in smooth-hole conditions, variations in invasion radius can excite 2D induction responses on the deep logs that make getting R_t problematic. In this case the laterolog is the preferred instrument because the invaded zone degrades the induction response in much the same way as an enlarged borehole.

$R_{xo} < R_t$

Where the contrast between R_{xo} and R_t is less than a factor of 50 both the induction and laterolog instruments yield valid responses (provided the borehole conditions discussed earlier are met). However, this does not mean that they will indicate the same formation resistivity value. Differences between the two indicate that we need to look in greater detail at the formation being measured to determine why the tools respond differently. BBE

There are a number of influences on the response of these

resistivity instruments that are not taken into account in the real-time "quick-look" processing available at the wellsite. These include

- shoulder-bed effects
- dipping beds
- formation anisotropy.

Shoulder-Bed Effects

All formation resistivity instrument responses assume a basic formation model. In the simplest of cases this involves an infinitely thick bed, such as is shown in Figure 8, with invasion as the only explanation for separation of the curves. All resistivity interpretation products available at the wellsite today apply this model to extract R_t and R_{xo} values from the instrument responses. The use of bucking, or focusing, currents in laterolog tool design and signal processing in induction response computation ensures that the instruments respond primarily to the formation directly in front of the tool. In most cases these focusing methods are sufficient to ensure that the 1D formation approximation is sufficiently accurate to explain the tool response and thus derive an accurate resistivity profile.

However, in layers with high resistivity contrast to their adjacent layers, this 1D assumption can lead to errors, since the "shoulder-bed effects" are not taken into account by the simple formation model. This is a particular problem for laterolog-type tools, where a 2D model is required to describe the interaction between the tool and the formation (Figure 9). The HRLA current flow assumed in the 1D radial inversion is close to that in a homogeneous formation, shown in Figure 10. For laterologs, the presence of significant resistivity contrast between layers results in defocusing of the currents from the tool. The currents follow the path of least resistance, as shown in the "antisqueeze" example in Figure 11. In this case the comparatively low resistivity of the beds above and below the interval of interest allow the currents to "leak off" into the shoulder beds, distorting the current distribution. Since the 1D computation of formation resistivity assumes that the current distribution is as in Figure 9, this distortion will result in significant underestimation of the formation resistivity and hence reserves-in-place. In this case a more complex formation model is required to account for the shoulder beds. Application of a 2D-formation model simultaneously accounts for borehole, shoulder-bed and invasion effects when solving for R_t, yielding a more accurate formation resistivity.

The effect of finite bed thickness on both array laterolog and array induction responses needs to be taken into account when considering which instrument to use for formation resistivity evaluation. The computed HRLA and AIT responses to an 8-ft layer with $R_t = 100$ ohm-m, $R_{xo} = 10$ ohm-m, and an invasion radius of 20 in., surrounded by shoulder beds of 1 ohm-m, can be seen in Figure 12. Despite the job planner, shown in Figure 13, indicating that both instruments yield valid results, it is obvious that further processing is required to extract accurate formation resistivities since the real-time processing of neither induction nor laterolog tools takes into account all the possible influences on the measurements. The results of the advanced processing are shown in Figure 14. Maximum Entropy Resistivity Log INversion (Merlin), coupled with 1D radial inversion, produces a close estimate of the formation parameters, while 2D inversion of the HRLA data yields a result even closer to the initial model.

It should be noted that the HRLA 2D inversion technique inverts the data into a rectangular bedding profile of the same type used in the model, while the Merlin inversion model assumes a sequence of very thin layers. This latter assumption produces "transitions" at the bed boundaries, as seen in Figure 14. Work to extend the 2D inversion software to include the AIT-family tools in vertical wells is under way. However, for deviated wells with invasion, Merlin processing followed by 1D radial inversion will remain the only way to interpret invasion with induction tools.

AIT log response can show anomalies in the presence of high shoulder-bed contrast coupled with high-conductivity (< 2 ohm-m) shoulders. This is a result of the use of the Born approximation to define the responses used for the current real-time log processing. This focusing, which includes contributions from many depth intervals around the tool, works best when the instrument is in a low-to-moderate contrast environment. With shoulder resistivities below 2 ohm-m coupled with shoulder-bed contrasts above 50:1, the Born-based tool response is poor. A new field processing which does not use the Born approximation has been developed to address these issues, especially in high-contrast formations when OBM has been used. An example of the new processing compared to the Born-based processing is shown in Figure 15. The high contrast between the reservoir resistivity (100 ohm-m) and that of the conductive shoulder beds (0.7 ohm-m) causes the standard AIT responses to overshoot in the resistive reservoir. The new logs are well behaved in these difficult induction-logging environments. It should be noted that, if water-based mud is used, the HRLA tool is the tool of choice for this difficult envi-

ronment. However, when OBM is used, we have to rely on induction measurements.

Dipping Layer Effect

The focusing mechanisms of both laterolog and induction instruments assume that the layers are perpendicular to the axis of the tool. The presence of relative dip between the axis of the tool/borehole and the formation layers introduces further complexity to accurate resistivity evaluation. This relative dip can be due to a vertical borehole through dipping layers, a deviated borehole through horizontal layers, or a combination of the two. In this case a 3D-formation model, such as that shown in Figure 16, must be applied to explain the responses from the resistivity instruments and hence extract a more accurate R_t. For the array laterolog 3D processing is available in the HRLA2D software. Modeling for AIT tools in 3D formations is available with the SLDMINV modeling code (Anderson *et al.*, 1999).

For AIT responses the maximum-entropy Merlin inversion (Barber *et al.*, 1999b) can be used to account for the effect of dipping layers on the response of the instrument. Figure 17 shows Merlin processing of AIT data in a well with 65° relative dip between the formation layers and the tool/borehole axis. The field processing (designed for 0° dip) shows artifacts and we know it does not read correctly. The processed results show coherent resistivity separation in the top zone and a dramatic increase in estimated R_t.

Anisotropy

The borehole and formation resistivities to which resistivity instruments respond have traditionally been subdivided into the equivalent resistivities, R_m, R_{xo}, and R_t, as shown in Figure 18. However, this allocation of equivalent resistivities may not be sufficient to accurately describe the resistivity distribution in the formation. The uninvaded formation resistivity, R_t, for example, may vary in each of the three spatial dimensions, as indicated graphically in Figure 18. In a vertical borehole with horizontal layers, induction instruments will be more sensitive to R_{t1} and R_{t2}, while laterolog instruments, with currents returning to the tools above and below the center of the instrument, will be sensitive to a combination of R_{t1} and R_v. For the known sources of anisotropy, sand-shale layering and clean-sand grain-size layering (Klein *et al.*, 1995), the anisotropy of the invaded zone will be greatly reduced. Modeling of cases with isotropic invasion and anisotropic uninvaded zones show that sensitivity of the RLA5 curve to anisotropy is little affected by isotropic invasion. Using these observed responses, differences between the laterolog and logs should allow us to detect such vertical anisotropy.

Recent work has shown that in the "overlap zone," the responses of the array laterolog and array induction can be integrated to yield an estimate of the resistivity anisotropy. Figure 19 shows the modeling of an invaded anisotropic formation with $R_v > R_h > R_{xo}$. The AIT and HRLA responses to this formation are also shown. Solving for R_t using a step-invasion profile model on the AIT data, we see that the AIT tool responds primarily to the horizontal resistivity, R_h, as shown in Figure 20. Using the R_h found, we now solve to find the value of R_v at each level that accounts for the RLA5 response of the HRLA. The R_{xo}, R_h, and R_v found by this processing are shown in Figure 21. While there are obviously shoulder-bed effects at the edges of the invaded zones, the ability to detect the presence of resistivity anisotropy in vertical wells is clearly displayed. Although logging conditions were not ideal for the AIT tool, Figure 22 shows AIT and HRLA logs in a well in a sand reservoir. Figure 23 shows the results of the anisotropy inversion. Ongoing development of this methodology should allow quantitative evaluation of resistivity in vertical wells where borehole and formation conditions fall in the "overlap" region of the two tools.

Other Complex Formation Models

The data content of array measurements also allows detection and evaluation of complex invasion profiles such as ramp and annulus profiles. In addition to accounting for shoulder-bed, dipping-bed, and anisotropy effects, future processing using these array measurements will enable the evaluation of more complex subsurface geometries, such as the azimuthal variation in resistivity often seen in horizontal wells.

Conclusions

Selection of the appropriate resistivity evaluation tool is crucial to ensuring that the best estimate of formation resistivity is delivered in real time. Improvements in electronics, materials, and processing have significantly increased the operating range of the latest array-resistivity instruments in comparison to their dual-measurement predecessors. New selection aids such as a Web-based job planner and real-time LQC flags have been developed to further aid in determining the appropriate ranges of operation. BBI

In some cases, the simplifying assumptions used to enhance wellsite-processing speed do not produce the optimum answer, such that even the tool best fitted to the

environment requires post-processing. In such cases the additional information available in the array measurements is critical for post-processing algorithms which more accurately accounts for influences on the tool responses. Processing such as HRLA2D for the HRLA data and Merlin for the AIT data can substantially enhance formation resistivity evaluation and hence reserves-in-place calculations by accounting for influences such as shoulder-bed and dipping-bed effects.

The recent introduction of the array laterolog tool has delivered a new wave of resistivity evaluation information to complement the array induction instruments. Where borehole environment conditions permit, differences in their responses can yield a great deal of information about formation resistivity distributions and hence hydrocarbon saturations which may otherwise have been missed.

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About the Authors

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Ollivier Faivre graduated from Ecole Polytechnique in 1973. After working as a field engineer and log analyst he joined the Schlumberger-Riboud Product Center in 1981 in new tool interpretation. He is currently manager of the Tool Evaluation group.

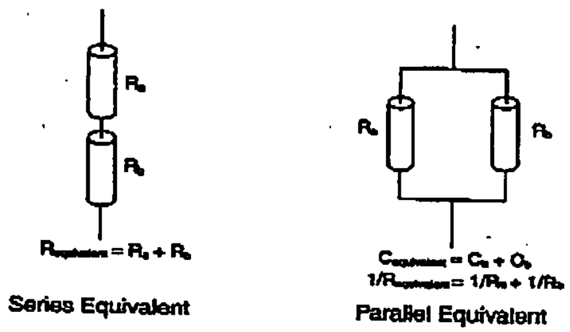

Figure 1. Electrical equivalent for resistances in series and parallel.

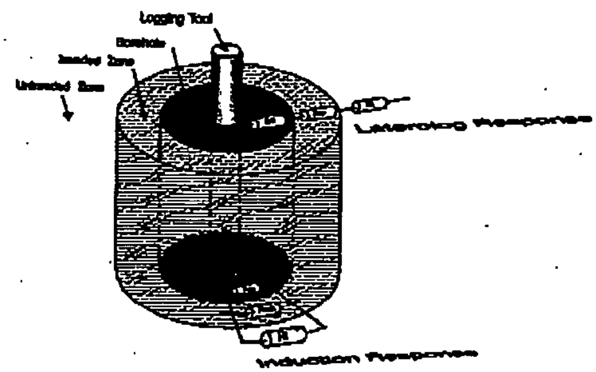

Figure 2. Laterolog instruments are sensitive to the series of resistivities that the measure currents encounter. Induction instruments are sensitive to formation conductivities, which can also be expressed as being sensitive to the parallel resistivities.

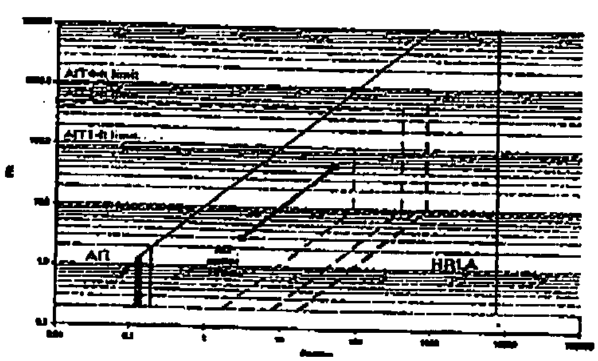

Figure 3. Web-based job planner that indicates the valid operating ranges for the AIT Array Induction Tool and HRLA High-Resolution Laterolog Array tool in an infinite, homogeneous, uninvaded formation. The limits vary according to the borehole size, tool position and R_t/R_m ratio entered by the user. A red line is plotted between the R_t/R_m and R_{xo}/R_m values to indicate the resistivity range expected in a given interval. This allows the user to judge whether the resistivities fall in the AIT range, the HRLA range or in the overlap zone (as is shown in this case), where environmental conditions allow valid measurements by both induction and laterolog instruments.

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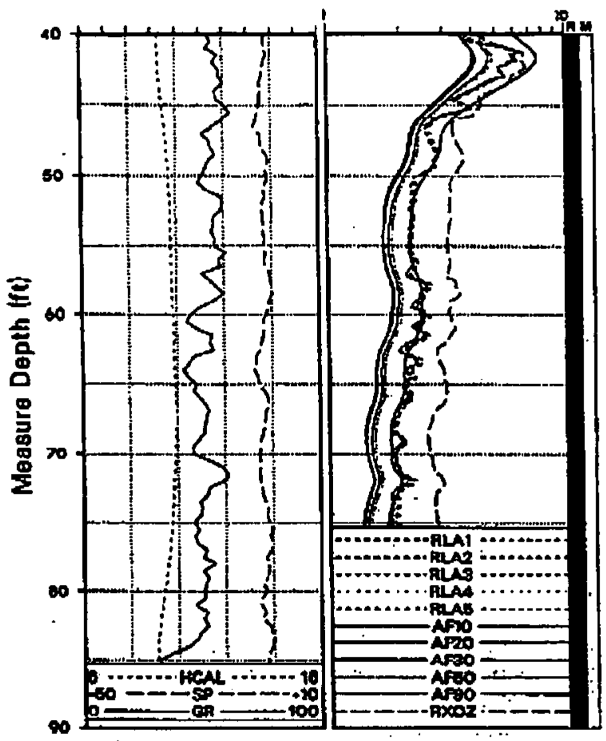

Figure 4. Differences in the laterolog and induction responses in this formation can be explained by a thin zone of high resistivity near the wellbore, possibly caused by formation damage during drilling.

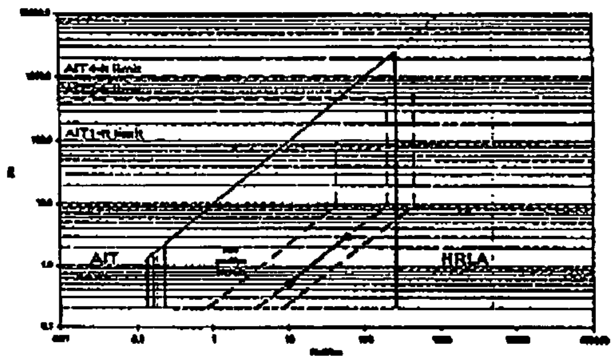

Figure 5. Resistivity job planner indicating that both the HRLA and 4-ft AIT responses should give valid formation resistivity information in this borehole and tool configuration.

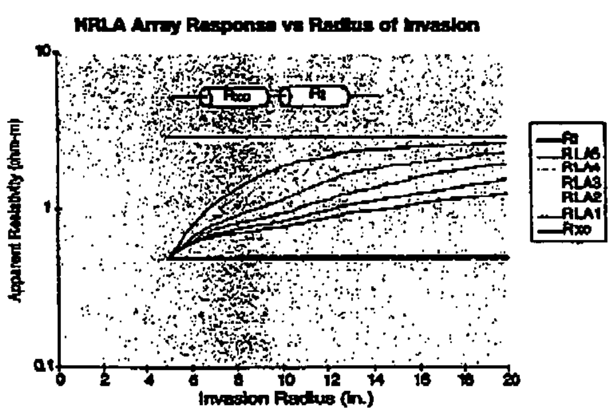

Figure 6. HRLA array response in a piston invasion profile with $R_t = 0.5$ ohm-m and $R_{xo} = 3$ ohm-m.

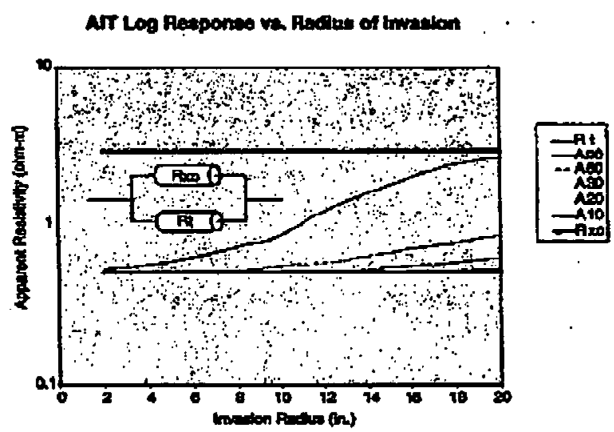

Figure 7. AIT array response in a piston-invasion profile with $R_t = 0.5$ ohm-m and $R_{xo} = 3$ ohm-m.

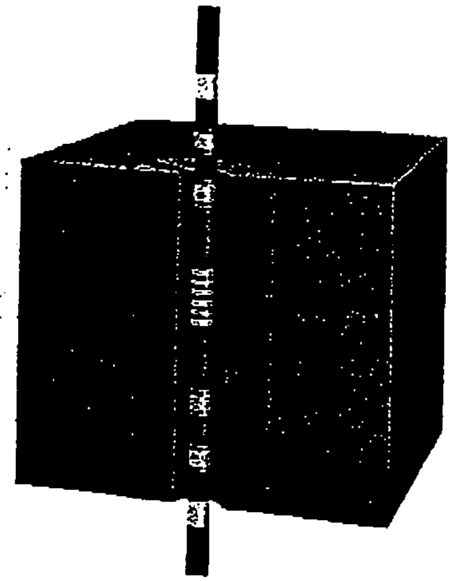

Figure 8. Simple 1D radial formation model.

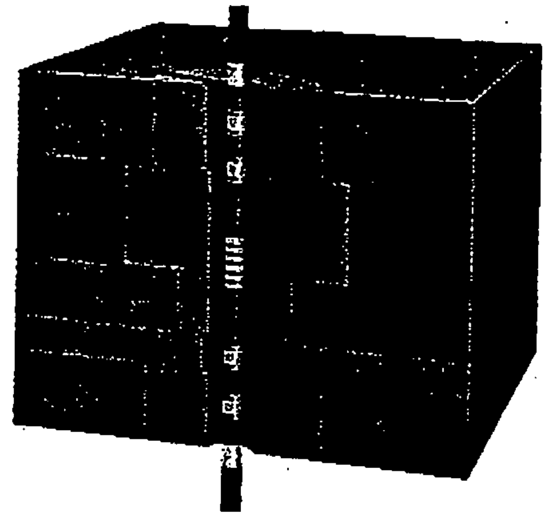

Figure 9. A 2D-formation model simultaneously accounts for borehole, shoulder, and invasion effects (as in Fig. 11).

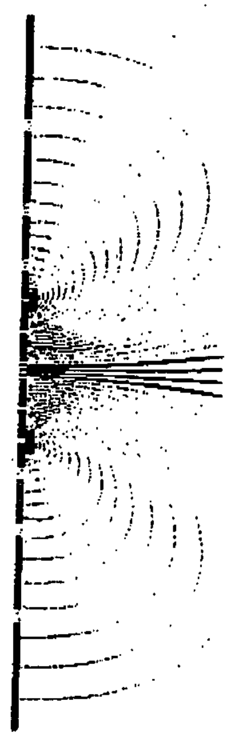

Figure 10. HRLA current flow lines in a homogeneous formation.

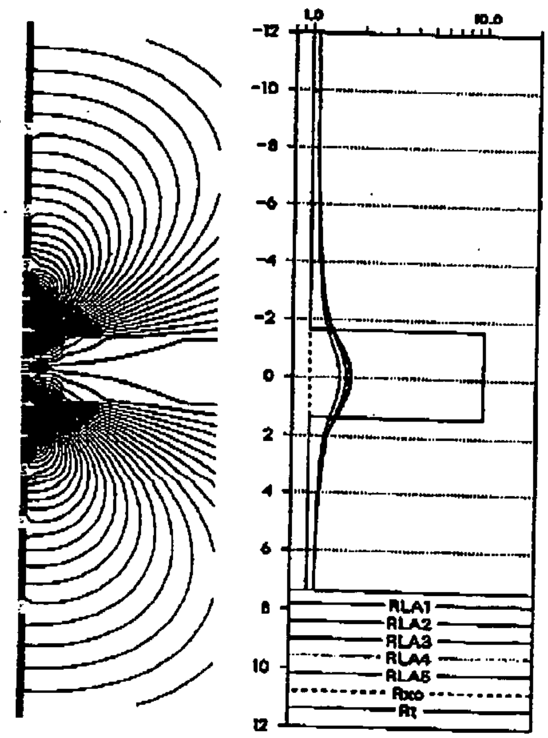

Figure 11. Current lines showing antisqueeze shoulder effect. R_t = 10 ohm-m; R_{xo} = 1 ohm-m; invasion radius = 20 in.; and bed thickness is 3 ft. Log on right shows array laterolog response in this case, indicating severe shoulder effect.

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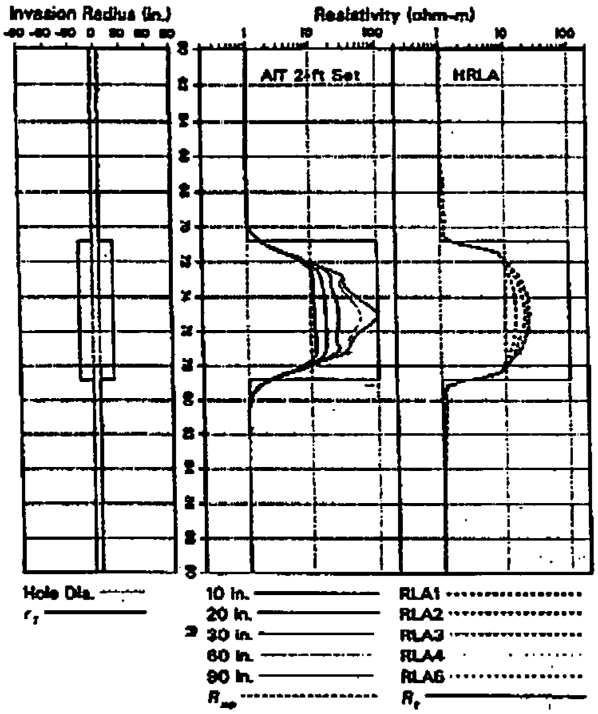

Figure 12. Finite bed thickness effects on HRLA and AIT instruments.

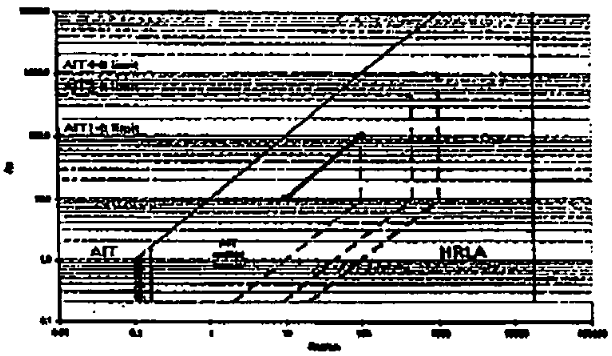

Figure 13. Operating envelope for the center bed conditions shown in Figure 12.

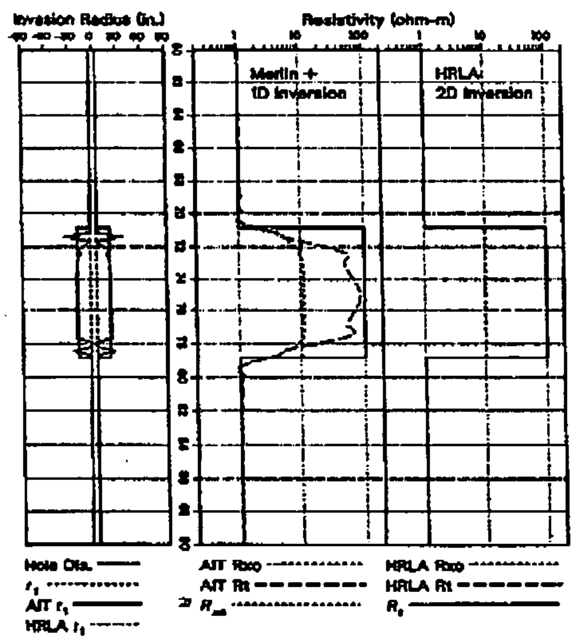

Figure 14. Results of 2D inversion on the HRLA data compared with Merlin processing followed by a 1D radial inversion of the AIT data.

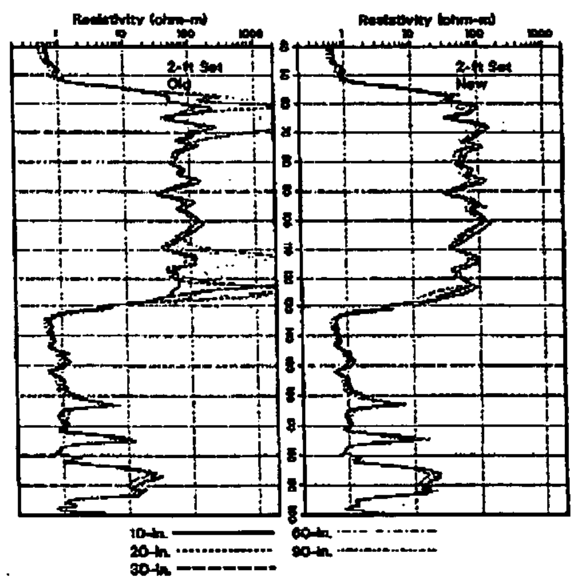

Figure 15. AIT logs in a high-contrast, low-resistivity shoulder situation. Born-based field logs overshoot; new non-Born logs behave well.

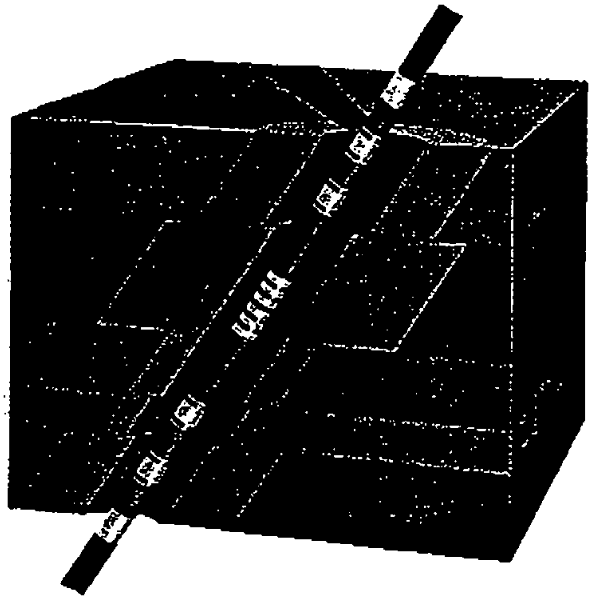

Figure 16. 3D formation model showing layers and invasion around a deviated wellbore.

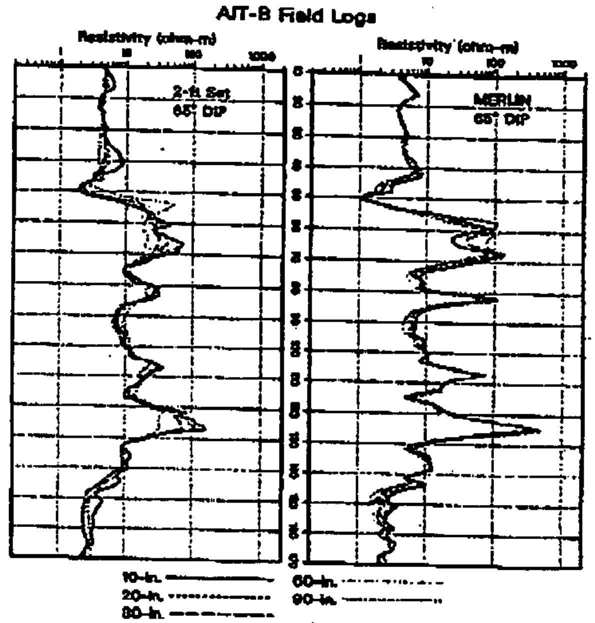

Figure 17. AIT field logs in a 76° deviated well compared with Merlin logs processed at 65° relative dip.

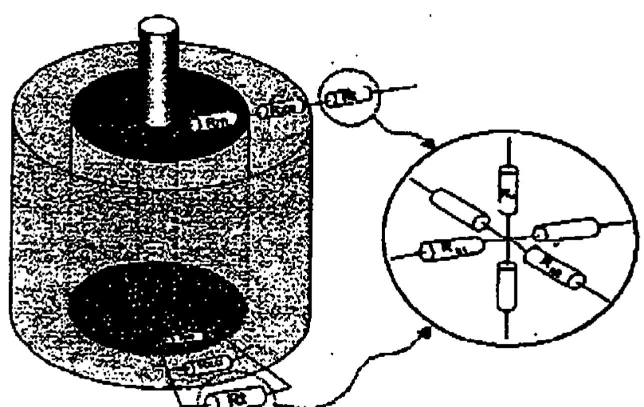

Figure 18. The equivalent uninvaded formation resistivity, R_t, may be an oversimplification of an anisotropic formation resistivity distribution. Induction and array instruments will respond differently to the resistivity components because of the difference in the physics of the instruments.

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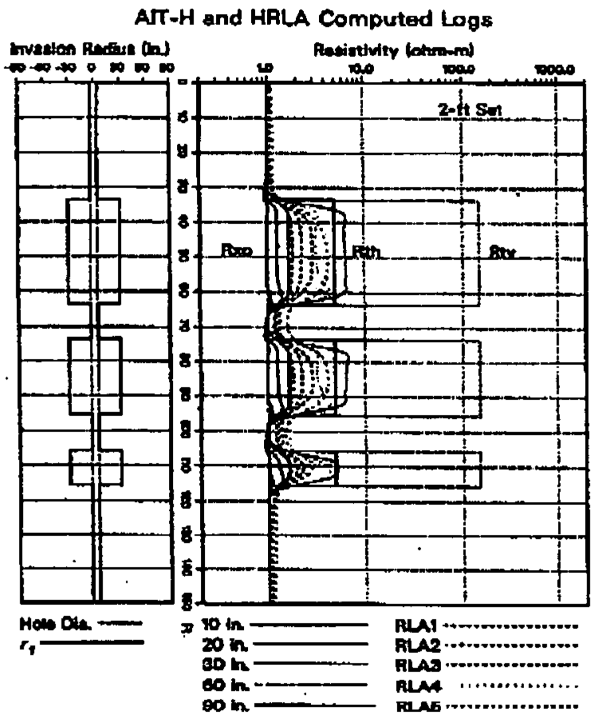

Figure 19. AIT-H and HRLA data in a 2D formation with invaded, anisotropic layers of varying thickness.

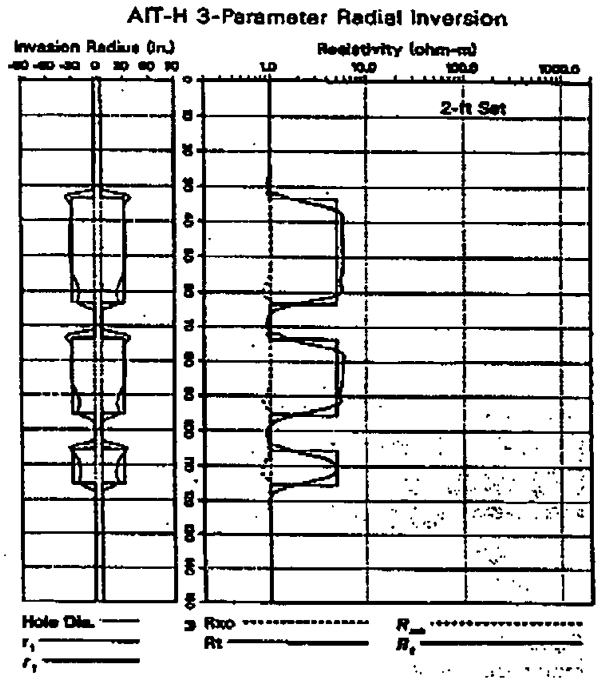

Figure 20. Inversion of AIT data from the scenario shown in Figure 19 using a step-invasion profile model.

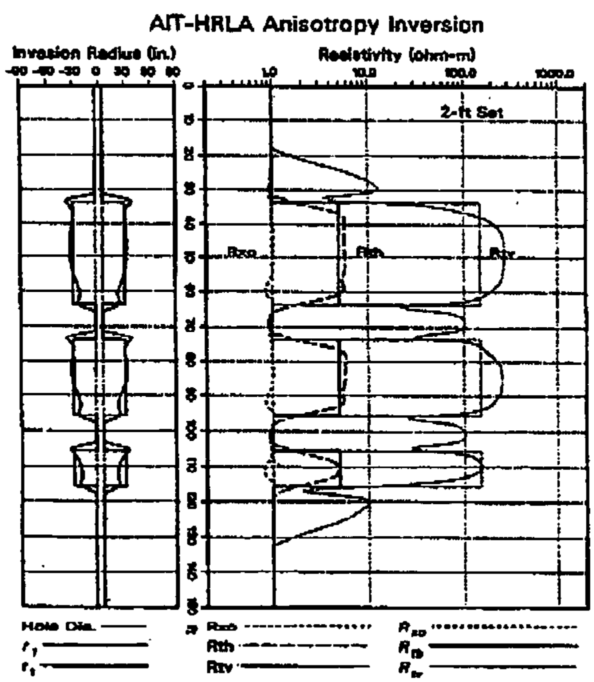

Figure 21. R_{tv} in the vertical-well formation model of Figure 18 extracted from a transform using AIT and HRLA data.

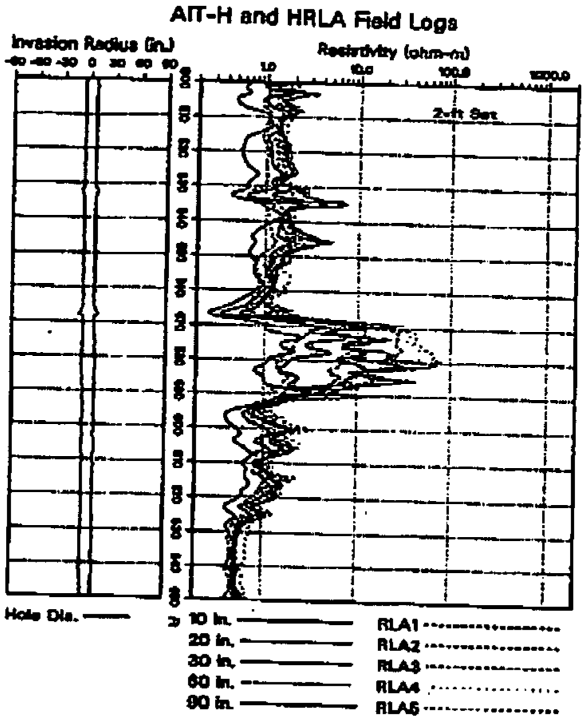

Figure 22. AIT and HRLA data in a well through a sand reservoir.

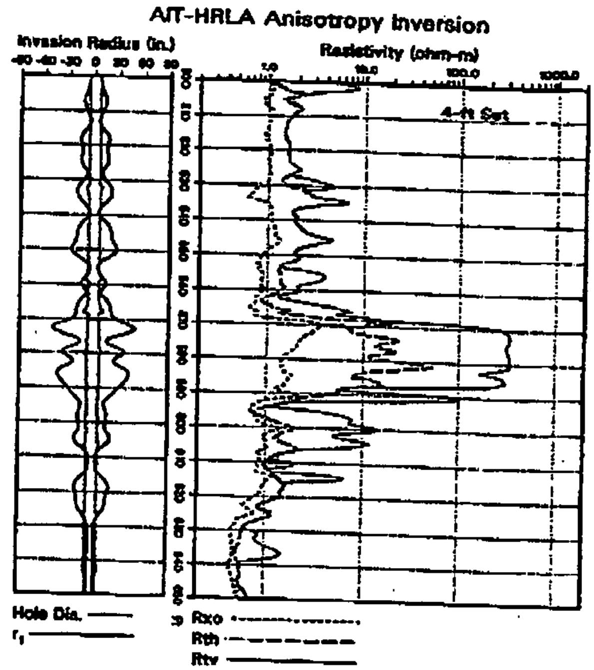

Figure 23. Results of the inversion of AIT and HRLA data for anisotropy in the well of Figure 22.

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